

METHOD FOR TRANSMITTING AND RECEIVING ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING SIGNAL AND APPARATUS THEREFOR

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BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a signal transmitting method and apparatus, and more particularly, to a signal transmitting method and apparatus by which an
10 orthogonal frequency division multiplexing (OFDM) method is improved.

2. Description of the Related Art

As a transmission rate is increased when data is transmitted through a wire or wireless channel, multipath fading or intersymbol interference (ISI) is increased, so that reliable data transmission cannot be expected. Orthogonal frequency division multiplexing (OFDM) and discrete multitone (DMT) are resistant to the multipath
15 fading and ISI and their band efficiencies are high, so that they are adopted in the signal transmitting method of a digital audio broadcast (DAB) and digital television (TV) in Europe, and they are used for an asymmetric digital subscriber line (ADSL) and a universal asymmetric digital subscriber line (UADSL) in U. S. A.

FIG. 1 shows a typical OFDM signal transmitting procedure. A series of input data bits b_n is encoded to sub-symbols X_n by an encoder 102. A series of X_n is converted to N-sized vectors or blocks by a serial-to-parallel converter 104. A pilot tone adder 105 adds M pilot tones P_i ($i=1, \dots, M$) to X_n to achieve channel estimation in a receiving side. The output of the pilot tone adder 105 is N-point
20 inverse fast Fourier transformed by an N-point inverse fast Fourier transformer (N-IFFT) 106, to N time domain signal x_k . Here, n indicates a frequency domain index, and k indicates a time domain index.

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$$x_k = \frac{1}{N} \sum_{n=0}^{N-1} X_n e^{j2\pi kn/N}, \quad k=0, \dots, N-1 \quad \dots(1)$$

A parallel-to-serial converter 108 transforms the vectors or blocks composed of N elements to a series of time domain signals x_k . A cyclic prefix adder 110 copies the last G signals from the N signals and attaches them to the front of the N signals. The G signals are referred to as cyclic prefix. (N+G) signal samples compose an OFDM symbol block in a time domain. The OFDM symbol block is consecutively converted to analog signals through a digital-to-analog converter 112, and the converted analog signals are output after an intermediate frequency (I/F) process and a radio frequency (R/F) process. The above-described procedure is typical for signal transmission in an OFDM system. Here, the position of the encoder 102 may be exchanged with the position of the serial-to-parallel converter 104.

FIG. 2 shows a typical procedure for receiving OFDM signals. The received analog signals are converted to a base band signal $r(t)$ through an R/F process and an I/F process, and the analog signals are sampled through an analog-to-digital converter 202 to convert the base band signal $r(t)$ to a digital signal r_k . A cyclic prefix remover 204 detects the starting of the OFDM symbol block from the received signals to remove the cyclic prefix, and then outputs N signal samples. The serial-to-parallel converter 206 converts a series of signal samples to N-sized vectors or blocks and outputs the N-sized vectors or blocks to an N-point fast Fourier transformer (N-FFT) 208. The N-FFT 208 transforms time domain signal r_k to a frequency domain signal R_n .

$$R_k = \sum_{n=0}^{N-1} r_k e^{-j2\pi kn/N}, \quad n=0, \dots, N-1 \quad \dots(2)$$

The R_n can also be expressed by the following Equation 3:

$$R_n = X_n \cdot H_n + I_n + W_n \quad \dots(3)$$

wherein X_n denotes data including data and a pilot tone P_i , H_n denotes a channel response, I_n denotes intercarrier interference, and W_n denotes additive white Gaussian noise (AWGN).

A channel estimator 209 can obtain M channel responses from the output R_n of N-FFT 208 using the already-known pilot tone P_i as in Equation 4:

$$\hat{H}_{n,i} = \frac{R_{n,i}}{P_i} = H_{n,i} + \frac{[I_{n,i} + W_{n,i}]}{P_i}, \quad i=1, \dots, M, \quad n=1, \dots, N \quad \dots(4)$$

The channel estimator 209 estimates a channel distorted by linear interpolating a channel response of data symbols, from $\hat{H}_{n,j}$.

A frequency domain equalizer (FEQ) 210 compensates for signal deformation generated by the channel with respect to the output R_n of the N-FFT 208, using the output of the channel estimator 209 as the tap coefficient of the FEQ 210 for each frequency index n.

A detector 212 detects an original sub-symbol \hat{X}_n from the output Z_n of the FEQ 210. The parallel-to-serial converter 214 converts the N-sized vectors to a series of signals, and a decoder 216 decodes a bitstream of data \hat{b}_n . The above-described processes are typical for receiving signals of the OFDM system. Here, the position of the parallel-to-serial converter 214 may be exchanged with the position of the decoder 216. Also, the detection by the detector 212 and the decoding by the decoder 216 may be performed in one step.

Several sub-symbols X_n are added as shown in Equation 1, so that the time domain OFDM signal x_k has a Gaussian distribution according to the central limit theorem. As a result, the peak-to-average power ratio (PAR) of the signal is very high.

FIG. 3 shows the amplitude of the time domain OFDM signal when $N=256$ and X_n is a quadrature phase shift keying (QPSK) symbols. When the PAR is high, clipping or severe quantization noise may occur in the digital-to-analog converter of a transmission terminal. When signals are transmitted, clipping and non-linear distortion may occur in a high power amplifier (HPA) of the R/F stage to thereby rapidly deteriorate performance. If a HPA is restricted to operate at a low power intentionally to avoid this problem, the efficiency of the HPA and total system performance can be deteriorated.

The PAR of a j th OFDM symbol $x_{j,k}$ is defined as follows.

$$\zeta_j = \frac{\max_{0 \leq k \leq N} |x_{j,k}|}{\sigma_x} \quad \dots(5)$$

The peak power of the time domain OFDM signal is different in every symbol, so that the PAR can not be obtained beforehand and only the statistical characteristics can be obtained. FIG. 4 shows the probability $\Pr\{\zeta_j > \zeta_0\}$ of the PAR values of the OFDM system being higher than a predetermined value ζ_0 when N is changed to 2, 4, 8, 16, ..., 1024.

A maximum PAR generated by the OFDM system can be easily obtained through Parseval's theorem. The maximum PAR generated by the OFDM signal having N sub-symbols is as follows.

$$\zeta_j = \frac{\max_{j, 0 \leq k \leq N} |x_{j,k}|}{\sigma_x^2} \quad \dots(6)$$

Here, σ_x^2 indicates variance of the time domain signals.

$$\max_{j, 0 \leq k \leq N} |x_{j,k}| = \max_n |X_n| = C \quad \dots(7)$$

$$\sigma_x^2 = \sigma_X^2 / N \quad \dots(8)$$

Here, σ_X^2 is the variance of the frequency domain signal X_n , and $\max_n |X_n| = C$ can be obtained by the constellation of the sub-symbol X_n . Thus, the PAR of Equation 5 can be obtained as follows.

$$\zeta = \sqrt{N} \zeta_X \quad \dots(9)$$

Here, $\zeta_X = C/\sigma_X$ indicates a PAR of the given sub-symbol X_n , and is also the PAR of the conventional single carrier method since this method allows symbols to be transmitted without any conversion. Thus, Equation 9 shows a difference in

PARs between the signal of the OFDM system obtained by the multi-carrier method and the signal of the conventional single carrier method.

In the conventional OFDM system, an N-point IFFT/FFT is used, so that the PAR of the signal is very great. Thus, various methods for reducing the PAR of the OFDM signal have been developed. The conventional algorithm for reducing the PAR of the OFDM signal is simple and very effective when the size N of the OFDM symbol is small, however, inappropriate for when N is large. In the algorithm adopted when N is large, as the PAR decreases much, the complexity and the information loss are increased.

Methods for reducing the PAR of the OFDM signals using coding are disclosed in papers "Block Coding Scheme for Reduction of Peak to Mean Envelope Power Ratio of Multi-Carrier Transmission Schemes", Electronics Letters, vol. 30, No. 25, pp. 2098 ~ 2099, December 1994, by A.E. Jones, T. A. Wilkinson and S. K. Barton, "Simple Coding Scheme to Reduce Peak Factor in QPSK Multicarrier Modulation", electronics letters, vol. 31, No. 14, pp. 113 ~ 114, July 1995, by S. J. Shepherd, P.W.J. van Eetvelt, C.W. Wyatt-Millington and S. K. Barton, and "OFDM Codes for Peak-to-Average Power Reduction and Error Correction", proc. of Globecom '96, pp. 740 ~ 744, London, November 1996, by Richard D. J. van Nee. But, the above methods cannot be adopted for an OFDM symbol for which N is greater than 16.

A reduction in noise by a reduction in the amplitude of a signal is obtained by U. S. Patent Nos. 5787113 and 5623513 "Mitigating Clipping and Quantization Effects in Digital Transmission Systems", and papers "Mitigating Clipping Noise in Multi-Carrier Systems", proc. of ICC, '97, PP. 715 ~ 719, 1997. But, the above method requires a reduction in the amplitude of the signal, so that the signal to noise ratio of the receiving terminal is reduced, and the reduction in the PAR is not great.

In U.S. Patent No. 5610908 entitled "Digital Signal Transmission System Using Frequency Division Multiplexing", the phase of a desired frequency domain signal is restored to an initial phase, and signals around band edges are attenuated,

in order to reduce the peak power value. However, this method is disadvantageous in that as peak power is reduced, more information is lost.

A method for determining a value appropriate for a redundant frequency index to eliminate the peak of a time domain OFDM signal is disclosed in references
5 "Clip Mitigation Techniques for T1.413 Issue3", T1E1. 4/97-397, December 1997, by Allan Gatherer and Michael Polley, and "PAR Reduction in Multi-Carrier Transmission Systems", T1E1.4 VDSL, T1E1.4/97-367, December 8, 1997, by Jose Tellado and John M. Cioffi. Here, in order to increase reduction in peak power, the redundant frequency must be increased and thus information loss must be
10 increased.

Two methods for changing the frequency domain phase of the OFDM signal to reduce the time domain peak power are compared in reference "A Comparison of Peak Power Reduction Schemes for OFDM", proc. of Globecom '97, pp. 1-5, 1997, by Stefan H. Muller and Johannes B. Huber. By these methods, a hardware
15 configuration becomes complicated because various N-point IFFTs should be simultaneously performed. Information loss can be generated because phase change information must be transmitted together with data. Information in the phase change must be exactly detected by the receiving terminal.

In the conventional single carrier transmission method, PAR is not great and thus the above-described problems of the OFDM system are not generated. By the
20 conventional single carrier method, an equalizer is trained and operated in the time domain. When the data transmission rate is increased, signal interference by a channel is rapidly increased, so that the number of equalizer taps of the receiving unit must be increased. At this time, the training of the equalizer requires much time
25 and the operation thereof is complicated. However, the FEQ of the OFDM system is trained and operated in the frequency domain, where one tap is required per frequency and training and operation are very simple. Thus, the OFDM method is appropriate for high-speed data transmission. But, the PAR of the OFDM signal is great so that it is difficult for the OFDM method to be utilized.

30 In the OFDM system, a transmission signal received via channel, is distorted by the characteristics of the channel and the influence of AWGN or the like, so that

an accurate channel estimation is required to detect a transmitted signal from the distorted received signal. In particular, under a channel environment having severe fading, a channel changes more rapidly, so much transmission information cannot be decoded if the channel is not properly estimated.

5 A. Leke and John. M. Cioffi ["Impact of Imperfect Channel Knowledge on the Performance of Multicarrier Systems", GLOBECOM'98] discloses a signal-to-noise ratio (SNR) in the case in which an accurate channel estimation is not achieved in the OFDM system, and emphasizes the importance of channel estimation. However, this paper does not mention the details of a channel estimation method.

10 An existing method for estimating a channel in the OFDM system includes a method using a reference symbol or a method using a pilot tone. U.S. Patent No. 5771223, entitled "Method of Receiving Orthogonal Frequency Division Multiplexing Signal and Receiver Thereof" discloses a method using a reference symbol, and U.S. Patent No. 5771224, entitled "Orthogonal Frequency Division Multiplexing
15 Transmission System and Transmitter and Receiver Thereof" discloses an invention for estimating a channel using a reference symbol and a null symbol. The method of estimating a channel using a reference symbol is appropriate for an environment having little change in the characteristics of the channel, but causes many channel estimation errors in a channel environment having severe fading.

20 In U.S. Patent No. 5406551, entitled "Method and Apparatus for Digital Signal Transmission using Orthogonal Frequency Division Multiplexing", a pilot tone is added to data at regular intervals and transmitted in an already-known frequency domain, and, in the receiving stage, the pilot tone is detected in the frequency domain, and the degree of attenuation of a channel is estimated by linear
25 interpolation and compensated for. Linear interpolation, which is a general channel estimation method using a pilot tone, is suitable for the environment where a channel change is slow. However, when the channel change becomes severe, much fluctuation occurs between pilot tones added at regular intervals in the frequency domain in the transmitting stage, thus making a channel estimation error
30 worse. This problem can be overcome by U.S. Patent No. 5774450 entitled "Method of Transmitting Orthogonal Frequency Division Multiplexing Signal and Receiver

Thereof", paper of F. Tufvesson and T. Maseng ["Pilot Assisted Channel Estimation for OFDM in Mobile Cellular Systems, Vehicular Technology Conference, 1997], paper of M.J.F. Garcia, J. M. Paez-Borrillo and S. Zazo ["Novel Pilot Patterns for Channel Estimation in OFDM Mobile Systems over Frequency Selective Fading Channels", PIMRC, 1999], which disclose deformation of a pilot tone to reduce channel estimation error in an environment having a serious channel change while using linear interpolation.

U.S. Patent No. 5912876, entitled "Method and Apparatus for Channel Estimation", and U.S. Patent No. 5732068, entitled "Signal Transmitting Apparatus and Signal Receiving Apparatus using Orthogonal Frequency Division Multiplexing", are related to an encoded pilot signal generator and a clock/pilot signal generator, respectively. In these references, a pilot signal is generated by encoding, and is added to the time domain output signal of an N-IFFT in the transmitting step and transmitted. These references can obtain a better channel estimation performance than other inventions because of a margin obtained by encoding. However, these references do not consider the PAR at all, so that many problems are generated in actual system implementation.

SUMMARY OF THE INVENTION

To solve these problems, an object of the present invention is to provide an orthogonal frequency division multiplexing (OFDM) signal transmitting and receiving method and apparatus by which the PAR is greatly reduced compared to a typical OFDM method and an equalizer is simplified compared to a typical single carrier method.

Another object of the present invention is to provide an OFDM signal transmitting and receiving apparatus and method by which a pilot signal is added to a transmission signal in the time domain at a transmitting terminal, and a channel is estimated by inserting a virtual pilot tone into the received signal of the frequency domain at a receiving terminal.

To achieve the first object, the present invention provides a method for transmitting OFDM signals, the method including: (a) coding the OFDM signals; (b)

forming a block of N coded data and dividing the block into L M-sized small blocks, where N, M and L indicate integers of 1 or more, and $L = N/M$; (c) M-point inverse fast Fourier transforming the L small blocks; (d) combining L M-point inverse fast Fourier transformed blocks, and generating an N-sized inversely-transformed block; (e) attaching a cyclic prefix to the N-sized inversely-transformed block; and (f) transforming the blocks having the attached cyclic prefix, into an analog signal and transmitting the transformed analog signal.

To achieve the first object, the present invention provides a method of receiving OFDM signals, the method including: (a) digitally converting received OFDM signals and obtaining a signal sample from the transformed signals; (b) detecting the starting point of an N-sized signal sample block from the signal samples, and removing a cyclic prefix; (c) dividing the signal sample block into L M-sized small blocks, where N, M and L are integers of 1 or more, and $L = N/M$; (d) M-point inverse fast Fourier transforming the L small blocks; (e) combining the L M-point inverse fast Fourier transformed small blocks, and generating an N-sized transform block; and (f) detecting data from the N-sized transform block, and decoding the detected data.

To achieve the first object, the present invention provides an apparatus for transmitting signals includes apparatus for transmitting OFDM signals, the apparatus including: an encoder for encoding OFDM signals; a transmission deinterleaver for forming N encoded code data into a block, and dividing the block into L M-sized small blocks, where N, M and L are integers of 1 or more, and $L = N/M$; L M-point inverse fast Fourier transformers for M-point inverse fast Fourier transforming the L small blocks; a signal transmission interleaver for coupling L M-point inverse fast Fourier transformed small blocks, thereby generating an N-sized inverse transformed block; a cyclic prefix adder for adding a cyclic prefix to the N-sized inversely transformed block; and a digital-to-analog converter for analog-transforming the inversely-transformed block to which the cyclic prefix is added and transmitting the analog-transformed signal.

To achieve the first object, the present invention provides an apparatus for receiving OFDM signals, the apparatus including: an analog-to-digital converter for

obtaining signal samples by digital-converting received OFDM signals; a cyclic prefix remover for finding the starting point of an N-sized signal sample block from the signal samples, and removing a cyclic prefix; a signal receiving deinterleaver for dividing the signal sample block into L M-sized small blocks, where N, M and L are integers of 1 or more, and $L = N/M$; L M-point fast Fourier transformers for M-point fast Fourier transforming the L small blocks; a signal receiving interleaver for interleaving the L M-point fast Fourier transformed small blocks, thereby generating an N-sized transform block; a detector for detecting data from the N-sized transform block; and a decoder for decoding the detected data.

To achieve the second object, the present invention provides an apparatus for transmitting OFDM signals, the apparatus including: a pre-processor for encoding an input data sequence and converting the encoded data to parallel data; a block signal domain transformer for dividing the encoded data into blocks of predetermined sizes, inserting "0" at the first data position of each block, transforming each block into a time domain signal, and combining time domain signals; a pilot signal adder for converting pilot tones, which are to be inserted at positions other than a predetermined position among the positions at which "0" has been inserted in the block signal domain transformer, into time domain pilot signals, and adding the pilot signals to the time domain signals output by the block signal domain transformer; and a post-processor for converting the resultant signals of the pilot signal adder to serial signals, adding a cyclic prefix to each of the converted signals, converting the resultant signals to analog signals, and transmitting the analog signals.

To achieve the second object, the present invention provides an apparatus for receiving OFDM signals, the apparatus including: a pre-processor for converting a received OFDM signal to a digital signal, removing a cyclic prefix from the digital signal, converting the resultant signal to parallel signals of predetermined sizes, and transforming each of the parallel signals to a frequency domain signal; a channel estimator for inserting virtual pilot tones at predetermined positions of the frequency domain signal, extracting the virtual pilot tones and pilot tones added upon transmission, and estimating channel characteristics from the extracted virtual pilot

tones and pilot tones; an equalizer for compensating for distortion of the output signal of the pre-processor caused by a channel, according to the estimated channel characteristics; an intermediate processor for converting the output signal of the equalizer to a time domain signal and removing pilot signals from the time domain signal; a signal domain transformer for transforming the output signal of the intermediate processor to a frequency domain signal; and a post-processor for detecting transmission data from the frequency domain signal, converting the detected data to serial data, and decoding the serial data.

To achieve the second object, the present invention provides a method for transmitting OFDM signals, the method including: (a) encoding an input data sequence, and converting encoded data to parallel data; (b) dividing the encoded data into blocks of predetermined sizes and inserting "0" at the first position of each block; (c) transforming each block to which "0" is inserted, to a time domain signal, and combining the time domain signals; (d) transforming pilot tones, which are to be inserted at positions other than a predetermined position among the positions at which "0" has been inserted, into time domain pilot signals, and adding each of the pilot signals to the time domain signal of each block; and (e) converting the resultant signal of the step (d) to a serial signal, adding a cyclic prefix to the converted signal, converting the resultant signal to an analog signal, and transmitting the analog signal.

To achieve the second object, the present invention provides a method of transmitting OFDM signals, the method including: (a) converting a received signal into a digital signal, removing a cyclic prefix from the digital signal, converting the resultant signal into parallel signals of predetermined sizes, and converting each parallel signal to a frequency domain signal; (b) inserting a virtual pilot tone at predetermined positions of the frequency domain signal and extracting the virtual pilot tone and pilot tones added upon transmission; (c) estimating channel characteristics from the extracted virtual pilot tone and pilot tones; (d) compensating for distortion caused by a channel with respect to the frequency domain signal, according to the estimated channel characteristics; (e) transforming a distortion-compensated signal into a time domain signal and removing pilot signals from the

time domain signal; and (f) detecting transmission data by transforming the resultant signals of the step (e) to a frequency domain signal, and converting the detected transmission data to serial data and decoding the serial data.

BRIEF DESCRIPTION OF THE DRAWINGS

The above objects and advantages of the present invention will become more apparent by describing in detail preferred embodiments thereof with reference to the attached drawings in which:

FIG. 1 is a block diagram of the structure of a conventional OFDM signal transmitting apparatus;

FIG. 2 is a block diagram of the structure of a conventional OFDM signal receiving apparatus;

FIG. 3 is a graph showing the amplitude of an OFDM signal;

FIG. 4 is a graph of PAR distribution of OFDM symbols when an N value is 2, 4, 8, 16, ..., 1024;

FIG. 5 is a block diagram of the structure of an OFDM signal transmitting apparatus according to an embodiment of the present invention;

FIG. 6 is a block diagram of the structure of an embodiment of the $L^*(M\text{-IFFT})$ of FIG. 5;

FIG. 7 shows an embodiment of the transmission deinterleaver of FIG. 6;

FIG. 8 shows a first embodiment of the transmission interleaver of FIG. 6;

FIG. 9 shows a second embodiment of the transmission interleaver of FIG. 6;

FIG. 10 is a block diagram of the structure of an OFDM signal transmitting apparatus according to another embodiment of the present invention;

FIG. 11 is a detailed block diagram of the block signal domain transformer of FIG. 10;

FIG. 12 shows the results of the operation of the "0" inserter of FIG. 11;

FIG. 13 shows the results of the operation of the transmission interleaver of FIG. 11;

FIG. 14 shows a result of the insertion of pilot signals of the time domain in view of the frequency domain;

FIG. 15 is a block diagram of the structure of an OFDM signal receiving apparatus according to an embodiment of the present invention;

FIG. 16 is a block diagram of the structure of an embodiment of the $L^*(M\text{-FFT})$ of FIG. 15;

FIG. 17 shows a first embodiment of the receiving deinterleaver of FIG. 15;

FIG. 18 shows a second embodiment of the receiving deinterleaver of FIG. 15;

FIG. 19 shows an embodiment of the receiving interleaver of FIG. 15;

FIG. 20 is a block diagram of a receiving apparatus that corresponds to the OFDM signal transmitting apparatus shown in FIG. 10;

FIG. 21 is a block diagram showing the channel estimator of FIG. 20 in greater detail;

FIG. 22 shows a result of the insertion of a virtual pilot tone in the frequency domain;

FIG. 23A is a graph showing the amplitude of a pilot tone in the transform domain;

FIG. 23B is a graph showing cutoff signal components to which "0" is added in the transform domain;

FIG. 24A is a graph showing the clipping probability with respect to a peak-to-average power ratio (PAR) in the OFDM signal transmitting/receiving apparatus shown in FIGS. 10 and 20;

FIG. 24B is a graph showing the clipping probability with respect to a PAR according to the prior art; and

FIG. 25 is a graph showing channel estimation error according to the present invention, in the prior art, and in the optimal case, with respect to a signal-to-noise ratio (SNR) in a channel having severe fading.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to FIG. 5, a signal transmitting apparatus according to an embodiment of the present invention includes an encoder 502, a serial-to-parallel converter 504, an L-distribution M-point inverse fast Fourier transformer ($L^*(M\text{-}$

IFFT)) 506, a parallel-to-serial converter 508, a cyclic prefix adder 510 and a digital-to-analog converter 512. The structure of the signal transmitting apparatus of FIG. 5 is similar to that of the conventional signal transmitting apparatus of FIG. 1. That is, the L*(M-IFFT) 506 instead of the N-IFFT 106 of the conventional signal transmitter is used, and the encoder 502, the serial-to-parallel converter 504, the parallel-to-serial converter 508, the cyclic prefix adder 510 and the digital-to-analog converter 512 according to the present invention correspond to the encoder 102, the serial-to-parallel converter 104, the parallel-to-serial converter 108, the cyclic prefix adder 110 and the digital-to-analog converter 112, respectively.

FIG. 6 shows an embodiment of the L*(M-IFFT) 506 of FIG. 5. The transmission deinterleaver 506a divides an N-sized input signal block into L M-sized small blocks. Then, each of the small blocks is M-point inverse fast Fourier transformed by L M-IFFTs 506b-1, 506b-2, ..., 506b-L. Here, $M \times L = N$. Then, the transmission interleaver 506c interleaves the outputs of the L M-IFFTs and then forms an N-sized block.

FIG. 7 shows an embodiment of the transmission deinterleaver 506a when $N = 8$, $M = 2$, and $L = 4$. FIGS. 8 and 9 show first and second embodiments of the transmission interleaver 506c when $N = 8$, $M = 2$ and $L = 4$.

L small blocks X_v^l , $l = 0, 1, \dots, L-1$ are composed of an input vector X_n .

$$X_v^l = X_{lM+v} = X_n, \quad n = lM + v, \quad l = 0, 1, \dots, L-1, \quad v = 0, 1, \dots, M-1 \quad \dots(10)$$

L M-IFFTs (506b-1, 506b-2, ..., 506b-L) receive X_v^l , $l=0, 1, \dots, L-1$ and perform M-point inverse fast Fourier transforms as shown in Equation 11 to output x_m^l , $l=0, 1, \dots, L-1$.

$$x_m^l = \frac{1}{M} \sum_{n=0}^{M-1} X_v^l e^{j2\pi mn/M}, \quad l=0, 1, \dots, L-1, \quad m=0, 1, \dots, M-1 \quad \dots(11)$$

In the transmission interleaver 506c, outputs x_m^l , $l = 0, 1, \dots, L-1$ of L M-IFFTs (506b-1, 506b-2, ..., 506b-L) are combined into a block to output x_k , $k=0, 1, \dots, N-1$.

Equation 12 indicates the first embodiment of Fig. 8, and Equation 13 indicates the second embodiment of Fig 9.

$$x_k = x_{lM+m} = x_m^l, k = lM+m, l = 0,1,\dots,L-1, m = 0,1,\dots,M-1 \quad \dots(12)$$

$$x_k = x_{mL+l} = x_m^l, k = mL+l, l = 0,1,\dots,L-1, m = 0,1,\dots,M-1 \quad \dots(13)$$

According to the signal transmitting apparatus of the present invention, the last G samples of N time domain signal samples $x_k, k=0,1,\dots,N-1$ are copied, the copied samples are attached as a cyclic prefix to the front of the N samples to make a time domain OFDM symbol block, and then the samples are converted to analog signals to be transmitted.

FIG. 10 is a block diagram of the structure of an OFDM signal transmitting apparatus according to another embodiment of the present invention. Referring to FIG. 10, the OFDM signal transmitting apparatus includes an encoder 502, a serial-to-parallel converter 504, a block signal domain transformer 1000, a pilot signal adder 1002, a parallel-to-serial converter 508, a cyclic prefix (CP) adder 510 and a digital-to-analog converter 512.

The operations of the encoder 502, the serial-to-parallel converter 504, the parallel-to-serial converter 508, the CP adder 510, and the digital-to-analog converter 512 are the same as those of FIG. 5.

The block signal domain transformer 1000 includes a transmission deinterleaver 1101, a "0" inserter 1102, L M-IFFTs 1103 and a transmission interleaver 1104, as shown in FIG. 11.

The transmission deinterleaver 1101 in the block signal region converter 1000 divides an N-sized vector or block into L M-sized vectors or blocks. That is, ML is equal to N. In this way, L blocks $X_v^l, l=0,1,\dots,L-1, v=0,1,\dots,M-1$ are obtained by Equation 10.

The "0" inserter 1102 inserts "0" into the first data in each block to avoid DC offset. FIG. 12 shows blocks each of which has "0" inserted at the first position.

The L M-IFFTs 1103 perform M-point IFFTs on the input

$X_v^l, l=0,1,\dots,L-1, v=0,1,\dots,M-1$ in each block as in Equation 11 to output

$X_m^l, l=0,1,\dots,L-1, m=0,1,\dots,M-1$.

The transmission interleaver 1104 combines the outputs

$X_m^l, l=0,1,\dots,L-1, m=0,1,\dots,M-1$ of the L M-IFFTs 1103 into a single block to output

$x_k, k=0,1,\dots,N-1$. The output of the transmission interleaver 1104 can be expressed as in Equations 12 and 13, depending on the combining method of the transmission deinterleaver 1101.

FIG. 13 shows an example of the sum of M-IFFTted signals. The pilot signal adder 1002 converts pre-designated pilot tones to time domain pilot signals and adds the time domain pilot signals at all positions except a position where $M=1$ and $L=1$, among positions of the M-IFFTted signals to which "0" is inserted in the block signal domain transformer 1000. FIG. 14 shows an example of the insertion of pilot signals of the time domain in view of the frequency domain.

FIG. 15 shows an embodiment of the signal receiving apparatus according to the present invention, which corresponds to the transmitting apparatus of FIG. 5.

The received analog signal $r(t)$ is sampled by an analog-to-digital converter 1502 to be converted to a digital signal r_k . A cyclic prefix remover 1504 finds the starting point of each of the OFDM symbol blocks of the received signal, removes the cyclic prefix, and outputs the N signal samples. A serial-to-parallel converter 1506 converts a series of signal samples to an N-sized vector to output the converted vector to an N-FFT 1508. The N-FFT 1508 transforms a time domain signal r_k to a frequency domain signal R_n . A FEQ 1510 multiplies the output R_n of the N-FFT 1508 by its tap coefficients for each frequency index n to thereby compensate for signal distortion caused by the channel, and outputs W_n . The N-IFFT 1520 N-point inverse fast Fourier transforms an input signal W_n to a time domain signal w_k . Here, a series of processes by the N-FFT 1508, the FEQ 1510 and the N-IFFT 1520 is an example of means for correcting distortion caused by a channel in a received signal r_k and obtaining a signal w_k , which may be realized by another filtering process.

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FIG. 16 shows an embodiment of an L-division M-point inverse fast Fourier transformer ($L \times (M\text{-FFT})$) 1522 of FIG. 15. In operation, a receiving deinterleaver 1522a divides an N-sized input signal block into L M-sized small blocks. Then, each of small blocks is M-point inverse fast Fourier transformed through the L M-FFTs (1522b-1, 1522b-2, ..., 1522b-L), where $M \times L = N$. Then, a receiving interleaver 1522c composes an N-sized block by interleaving the outputs of the L M-FFTs (1522b-1, 1522b-2, ..., 1522b-L). FIGS. 17 and 18 show first and second embodiments of the receiving deinterleaver 1522a when $N=8$, $M=2$ and $L=4$. FIG. 19 shows an embodiment of the receiving interleaver 1522c when $N=8$, $M=2$ and $L=4$. FIG. 17 shows the operation of the receiving deinterleaver 1522a of a signal receiving apparatus corresponding to the case in which a transmission interleaver 506c of a signal transmitting apparatus is implemented to operate as shown in FIG. 8. FIG. 18 shows the operation of the receiving deinterleaver 1522a of the signal receiving apparatus corresponding to the case in which a transmission interleaver 506c of a signal transmitting apparatus is implemented to operate as shown in FIG. 9. Equation 14 shows an embodiment of the operation of the receiving deinterleaver 1522a of FIG. 12, and Equation 15 shows an embodiment of the operation of the receiving deinterleaver 1522a of FIG. 13.

$$\omega_m^l = \omega_{lM+m} = \omega_k, k = lM+m, l=0,1,\dots,L-1, m=0,1,\dots,M-1 \quad \dots(14)$$

$$\omega_m^l = \omega_{mL+l} = \omega_k, k=mL+l, l=0,1,\dots,L-1, m=0,1,\dots,M-1 \quad \dots(15)$$

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The L M-FFTs (1522b-1, 1522b-2, ..., 1522b-L) receive $\omega_m^l, l=0,1,\dots,L-1$ and perform the M-point inverse fast Fourier transform of Equation 16, to thereby output $W_v^l, l=0,1,\dots,L-1$.

$$W_v^l = \sum_{m=0}^{M-1} \omega_m^l e^{-j2\pi mv/M}, l=0,1,\dots,L-1, v=0,1,\dots,M-1 \quad \dots(16)$$

Then, the receiving interleaver 1522c interleaves the output W_v^l , $l=0,1,\dots,L-1$ of the L M-FFTs (1522b-1, 1522b-2, ..., 1522b-L) to form an N -sized block Z_n , as in Equation 17:

$$Z_n = Z_{lM+v} = W_v^l, n=lM+v, l=0,1,\dots,L-1, v=0,1,\dots,M-1 \quad \dots(17)$$

A detector 1512 detects X_n from Z_n .

FIG. 20 is a block diagram of a receiving apparatus that corresponds to the OFDM signal transmitting apparatus shown in FIG. 10. Referring to FIG. 20, the OFDM signal receiving apparatus includes an analog-to-digital converter 1502, a CP remover 1504, a serial-to-parallel converter 1506, an N-FFT 1508, a virtual pilot signal inserter 2000, a channel estimator 2002, an FEQ 2004, an N-IFFT 2006, a pilot signal remover 2008, an $L^*(M\text{-FFT})$ 1522, a detector 1512, a parallel-to-serial converter 1514, and a decoder 1516.

The channel estimator 2002 includes a pilot signal extractor 2100, an L-FFT 2102, an adaptive low pass filter (LPF) 2104, a "0" padder 2106 and an N-IFFT 2108, as shown in FIG. 21.

The analog-to-digital converter 1502, the CP remover 1504, the serial-to-parallel converter 1506, the N-FFT 1508, the $L^*(M\text{-FFT})$ 1522, the detector 1512, the parallel-to-serial converter 1514, and the decoder 1516 operate the same as their counterparts of FIG. 15.

The virtual pilot tone inserter 2000 generates a virtual pilot tone and insert the same into a position where $M=1$ and $L=1$ in the output signal of the N-FFT 1508. The virtual pilot tone $P_{M=1,L=1}$ is obtained by calculating the average of a pilot tone at the position where $M=1$ and $L=2$ and that at the position where $M=1$ and $L=L$, among the pilot tones extracted by the channel estimator 2002 as in Equation 18:

$$P_{M=1,L=1} = \frac{(P_{M=1,L=2} + P_{M=1,L=L})}{2} \quad \dots(18)$$

FIG. 22 illustrates the insertion of a virtual pilot tone in the frequency domain. The channel estimator 2002 estimates a channel from a signal into which the

virtual pilot tone is inserted. The operation of the channel estimator 2002 will now be described in more detail with reference to FIG. 21. The pilot signal extractor 2100 extracts pilot tones from the output signal R_n of the N-FFT 1508, and normalizes the values of the extracted pilot tones together with the virtual pilot tone.

5 The L-FFT 2102 transforms the extracted pilot tones from the frequency domain to the transform domain by performing L-point FFT on the extracted pilot tones. The adaptive LPF 2104 cuts off pilot tones whose amplitudes are smaller than a mean noise level, among the pilot tones in the transform domain, depending on designed filter coefficients. FIG. 23A shows the amplitudes of pilot tones in the transform

10 domain. As shown in FIG. 23A, pilot tones whose amplitudes are smaller than the mean noise level are cut off.

The "0" padder 2106 adds "0"s to the signal components cut off by the adaptive LPF 2104. FIG. 23B shows an example of the cutoff signal components to which "0"s are added in the transform domain.

15 The N-IFFT 2108 transforms the output of the "0" padder 2106 to a signal of the frequency domain to obtain an estimated channel response.

The FEQ 2004 compensates for signal distortion, caused by a channel, in the output R_n of the N-FFT 1508, by using the estimated channel response value as its tap coefficients.

20 ~~The N-IFFT 2006 N-point fast Fourier transforms the output signal of the FEQ 2004 to a time domain signal w_k . The pilot signal remover 2008 removes the pilot signal added upon transmission.~~

FIG. 24A shows the clipping probability with respect to a PAR in the OFDM signal transmitting/receiving apparatus shown in FIGS. 10 and 20.

25 FIG. 24B shows the clipping probability with respect to a PAR according to the prior art. That is, FIG. 24B shows the clipping probability with respect to a PAR in the case where pilot tones are added in the frequency domain where N-IFFT has not been performed yet.

30 In each of FIGS. 24A and 24B, four different cases of a pilot tone of 1, a pilot tone of $1+1i$, a pilot tone of $3+3i$, and a pilot tone of 10 are applied for comparison. It can be seen from FIGS. 24A and 24B that the PAR in the present invention

increases very little even though the amplitudes of pilot tones are changed, while the PAR in the prior art significantly increases as the amplitudes of pilot tones vary.

FIG. 25 is a graph showing channel estimation error according to the present invention shown in FIGS. 10 and 20, channel estimation error in the prior art, and channel estimation error in the optimal case, with respect to signal-to-noise ratios (SNR) in a channel where severe fading occurs. Here, the prior art is based on linear interpolation.

As shown in FIG. 25, the present invention can significantly reduce the level of channel estimation error compared to the prior art, and achieves channel estimation error that is similar to that in the optimal case. A simulation made under the channel conditions of severe fading showed that the present invention achieves a bit error ratio (BER) which is only 0.5 to 1dB less than that of the optimal case.

According to the present invention, when $L=N$ and $M=1$, the input of $L*(M\text{-IFFT})$ 506 of FIG. 5 is the same as the output thereof so that signals in time domain are generated. Here, a serial-to-parallel converter 504 and a parallel-to-serial converter 508 of a signal transmitting apparatus are not required. Also, the input of $L*(M\text{-FFT})$ 1522 of FIG. 15 is the same as the output thereof. According to the method of transmitting signals of the present invention, signals in time domain are generated and the generated signals are transmitted and data in the time domain is detected, which is the same as the conventional method for transmitting single carrier signals. However, according to the signal transmitting method of the present invention, the signal transmitting apparatus adds a cyclic prefix to every N -sized block and the signal receiving apparatus removes the cyclic prefix from the received signal, and data is detected by processing of a $N\text{-FFT}$ 1508, a FEQ 1510 and a $N\text{-IFFT}$ 1520, which is different to the conventional method for transmitting single carrier signals. According to the present invention, an equalizer of the signal receiving apparatus operates in a frequency domain to thereby solve the problems generated when code processed by the equalizer is lengthened by the conventional single carrier signal transmitting method.

According to the present invention, signals in the time domain are generated by $L*(M\text{-IFFT})$ 506 so that the maximum PAR value of the signal is as follows.

$$\xi = \sqrt{N}\xi_x = \sqrt{N/L}\xi_x \quad \dots(19)$$

That is, compared to the conventional OFDM signal, the maximum PAR value of OFDM signal according to the present invention is reduced to $1/\sqrt{L}$. When $M = 1$, and $L = N$, the PAR value of the signal according to the present invention is the same as the value of the conventional method for transmitting single carrier signals.

According to the present invention, when $1 < M < N$, the PAR of the signal can be further reduced if the conventional method for reducing the PAR of the signal is applied together.

In the paper "OFDM Codes for Peak-to-Average Power Reduction and Error Correction", proc. of Globecom '96, pp. 740 - 744, London, November 1996, $N=16$ and two 8-symbol complementary codes are interleaved. The PAR of the signal in the conventional OFDM system is 3dB when $N=8$ and the 8-symbol complementary code is used, but 6.24dB when $N=16$ and two 8-symbol complementary codes are used. However, according to the present invention, when $N = 16$, $L = 2$ and $M = 8$, the PAR of the signal is 3dB, which is 3.24dB less than that obtained using the conventional methods. In the conventional method for reducing the PAR of the signal using a code, when N is increased, the decoder of the receiving terminal becomes very complicated so that N must be small. However, according to the present invention, the symbol of the large N can be divided into L small symbols and the divided symbols can be coded.

In the U.S. Patent Nos. 5787113 and 5623513 entitled "Mitigating Clipping and Quantization Effects in Digital Transmission Systems", when the peak power of the signal exceeds a predetermined clipping level, the total size of a corresponding OFDM symbol must be reduced, so that the power of the symbol must be reduced. In the method for reducing the PAR according to the present invention a block is divided to $L * M$ -sized small blocks so that the size of part of the symbol is reduced and the reduction in power of the total signal is smaller than that of the conventional method. When information of signal reduction is detected from the receiving terminal and the method for reducing PAR according to the present invention is

adopted, the information of signal reduction has an effect on corresponding blocks without having an effect on the total symbol.

Also, according to the present invention, the PAR can be reduced by adding pilot signals in the time domain to achieve channel estimation. Furthermore, a receiving apparatus inserts a virtual pilot tone in the frequency domain to reduce channel estimation error, so that a channel can be more accurately estimated.